Space Weather Impacts to Conjunction Assessment: A NASA Robotic Orbital Safety Perspective

Rich Ghrist, Russell DeHart (a.i. solutions)

Lauri Newman (NASA Robotic Conjunction Assessment Manager)

IMPACT Workshop| Santa Fe, NM | 29-31 January, 2013

Briefing Purpose

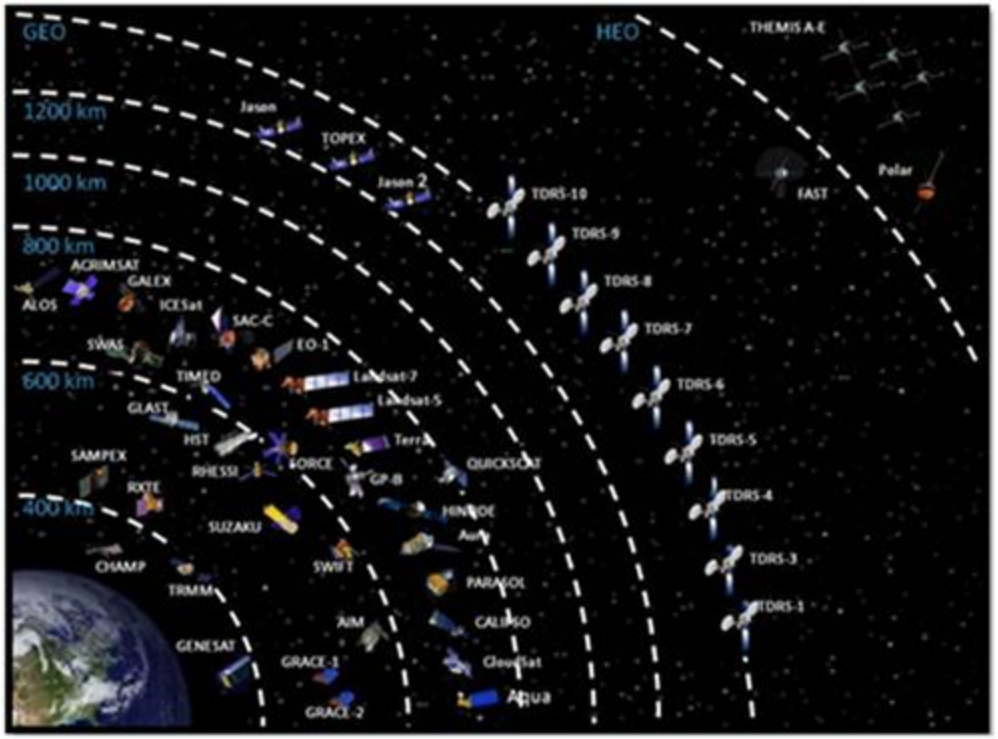
- Operational perspective: Present challenges that space weather poses for performing conjunction assessment mission
- Research perspective: Present NASA Robotic CARA research to date on efforts to characterize risk from changing space weather predictions on conjunction assessment

Agenda

- Background:
  - NASA Robotic CARA
  - Atmospheric Drag
- Time Offsets:
  - Empirical Evidence
  - Impact on Conjunction Assessment
- Conclusions and Questions

NASA Robotic Conjunction Assessment Risk Analysis (CARA)

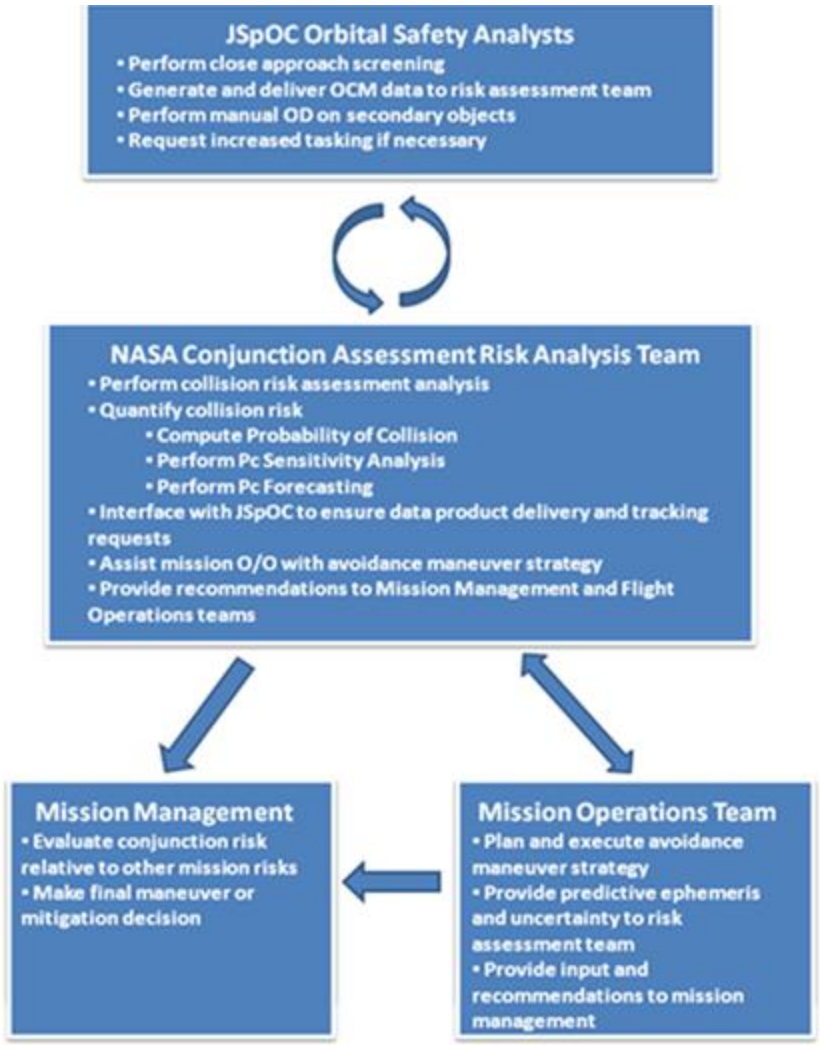
- CARA provides support to all operational NASA robotic missions
- Supports 67 missions, including
  - Earth Science Constellation
  - TDRSS
  - Hubble Space Telescope
- As well as a service to other agencies
  - NOAA for POES satellites
  - USAF for SBSS and DMSP satellites



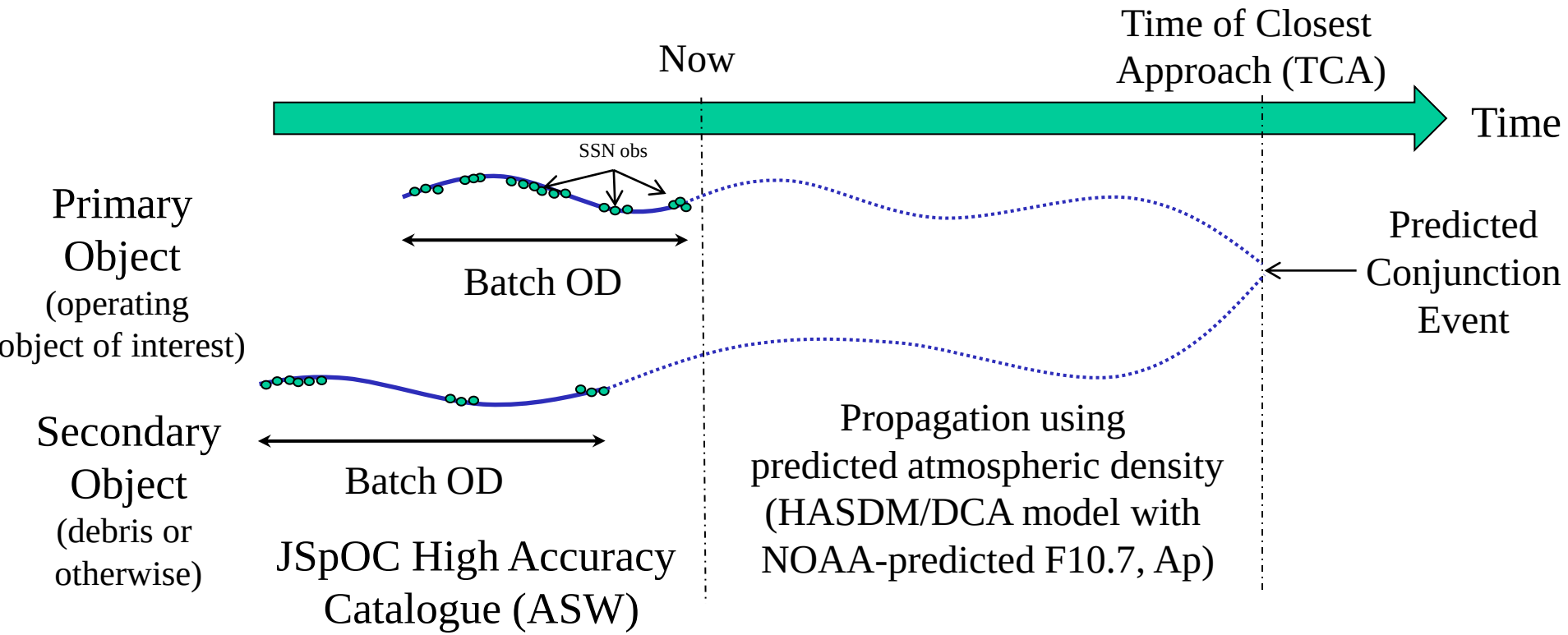
The Conjunction Assessment Risk Analysis mission at NASA GSFC is to protect NASA robotic assets from threats posed by other space objects while operating in the space environment through ensuring domain expertise, a robust concept of operations, and an operationally-responsive system to meet the expanding needs of the mission area

NASA Robotic CARA (con't)

- A ***conjunction*** is defined here to mean a local minimum in the difference between the position components of two trajectories – the closest point of approach
- ***Conjunction Assessment (CA)*** is the process of predicting conjunctions
- ***Conjunction Assessment Risk Analysis (CARA)*** is the process of analyzing the conjunction event to determine the associated risk to the asset
- ***Collision Avoidance*** is the process by which the risk associated with a conjunction event is mitigated – by a maneuver or other action

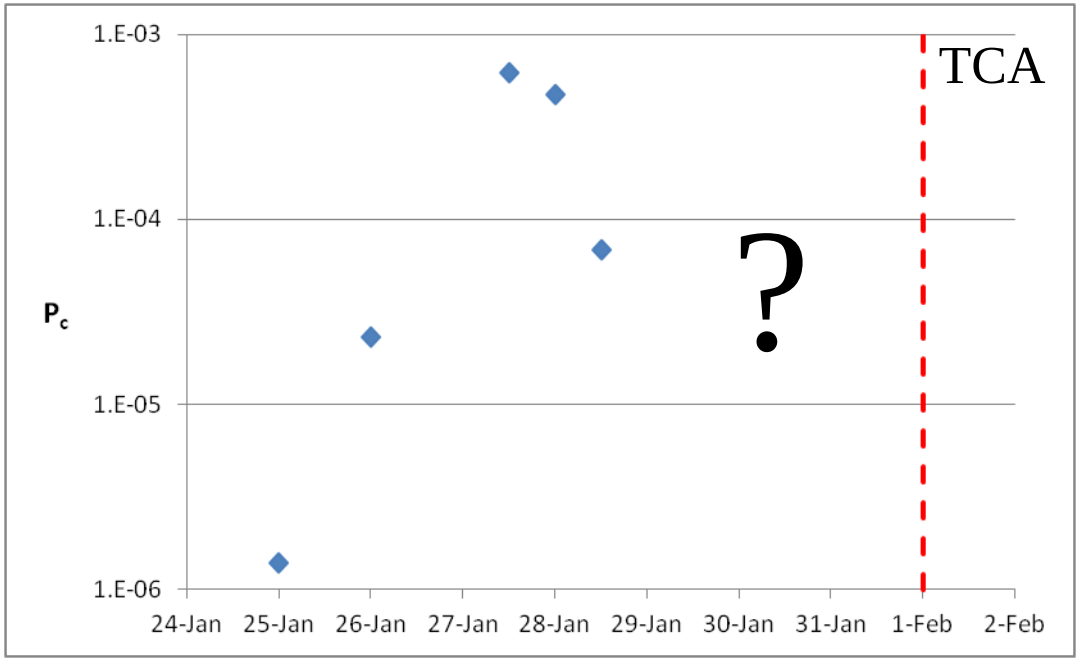


Conjunction Assessment: JSpOC Process and Products



- Orbital Conjunction Message (OCM):
  - Includes both object's state vector and position covariance at TCA
    - Allows computation of probability of collision (P_c)
  - May receive multiple OCMs over time from additional Space Surveillance Network (SSN) tracking

Space Weather and Conjunction Assessment: A Notional Event



25 Jan: first identification of possible conjunction on 1 Feb

27-28 Jan: P_c first increases to level of concern before starting to fall (looking safer)

29 Jan: Alert of a Coronal Mass Ejection (CME) heading for Earth on 31 Jan

Spacecraft owner/operator (O/O) wants to know if (and how) CME will impact conjunction event

- Does the new space weather prediction make this event safer or riskier?
- Might performing a maneuver make the conjunction event worse?

Space Weather and Conjunction Assessment: General Questions

- Are observed changes in conjunction event consistent with space weather changes?
- How does changing space weather predictions affect conjunction assessment predictions?
  - If state vectors and/or covariances impacted, this impacts P_c
  - How to enfold space weather uncertainty into conjunction assessment? How to communicate this to O/Os?
  - Assessment of current risk and mitigation strategies: too conservative, not conservative enough?

Agenda

- Background:
  - NASA Robotic CARA
  - Atmospheric Drag
- Time Offsets:
  - Empirical Evidence
  - Impact on Conjunction Assessment
- Conclusions and Questions

Background: Space Weather Impacts on Satellites

- Particle bombardment
  - Electrical charging
  - Ionization events
- Satellite disorientation
- Communication loss
- Increased atmospheric drag
  - Satellite position
  - Covariance size
- Ionospheric effects
  - Incomplete/inadequate ionospheric correction will impact range performance of SSN ground-based radar tracking
  - Could impact OD

Important to conjunction assessment

Focus of NASA Robotic CARA space weather research relates to atmospheric drag

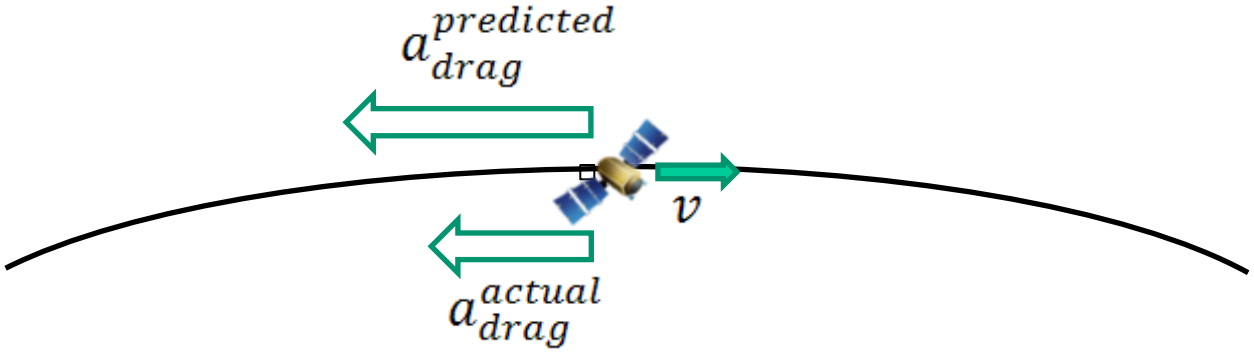
Background: Atmospheric Drag

- Atmospheric drag magnitude: $a_{drag} = \frac{1}{2}\beta\rho v^2$
  - $\beta = \frac{c_D A}{m}$ is ballistic coefficient

    ρ is atmospheric density

    $v \cong v_{\text{sat}}$
  - Solar cycle and space weather have strong impact on neutral atmospheric density
  - Increasing atmospheric drag impacts:
    - Frequency of "Drag Make-Up" maneuvers to stay in control box
    - Covariance size
  - Uncertainty in predicted atmospheric drag impacts:
    - Future satellite position predictions (next slide)

Background: Atmospheric Drag and Predicted Satellite Position



- Satellite will be at a different position if $a_{drag}^{actual} \neq a_{drag}^{predicted}$
  - Uncertainty in predicted atmospheric density not currently incorporated into propagation results
  - Uncertainty in ballistic coefficient incorporated in covariance
- Drag acceleration ~counter to satellite velocity
  - Change to drag primarily results in offset in along-track position
  - Equivalently can be represented as an early/late offset time

Atmospheric Drag and Covariance Size

- Analytic covariance growth model*:
  - Drag case (assuming no uncertainty in ρ):
    - Mean anomaly: $\sigma_M \approx \frac{3\dot{\varepsilon}_0}{2\sqrt{\mu a_0}}\left(\frac{\sigma_{\beta_0}}{\beta_0}\right)t^2$

      Quadratic growth in time
    - Semi-major axis: $\sigma_a \approx \frac{a_0^2\dot{\varepsilon}_0}{\mu}\left(\frac{\sigma_{\beta_0}}{\beta_0}\right)t$

    where

    $\dot{\varepsilon} = \vec{a}_{drag} \cdot \vec{v} = -\frac{1}{2}\beta\rho v^3$ = energy dissipation rate

    t = propagation time

    subscript 0 refers to epoch
- Higher drag in the *past* (during OD) leads to larger covariance size in *future* (at TCA)

* Extension of Hoots (AAS 11-579)

Atmospheric Drag and Covariance Size (con't)

- Effect of larger covariance on P_c:
  - At a snapshot of time: Most P_c values decrease but some P_c values (at small misses) increase*
  - As a function of time: Could delay determination of conjunction event being assessed as threat/non-threat until closer to TCA
    - "Classic" P_c time series curve for a miss slowly rises at first but rapidly falls-off near TCA as the covariances contract
    - Potential impact to conjunction mitigation timeline
      - Desirable to have clear recommendation before maneuver "go/no-go" decision

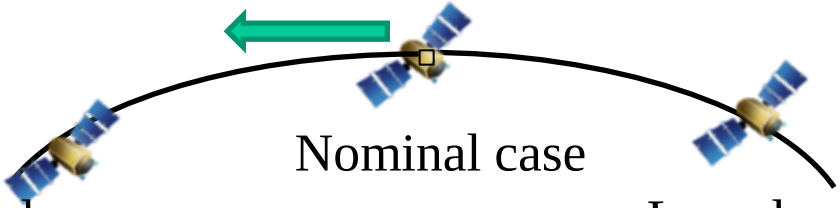
* Jenkin (AIAA 2002-1810), Frigm and McKinley (AIAA 2010-7823)

Agenda

- Background:
  - NASA Robotic CARA
  - Atmospheric Drag
- Time Offsets:
  - Empirical Evidence
  - Impact on Conjunction Assessment
- Conclusions and Questions

Time and Energy Offsets Between Predictions

- Predicted satellite location at TCA



Nominal case

More drag case
- Early
- Less orbital energy

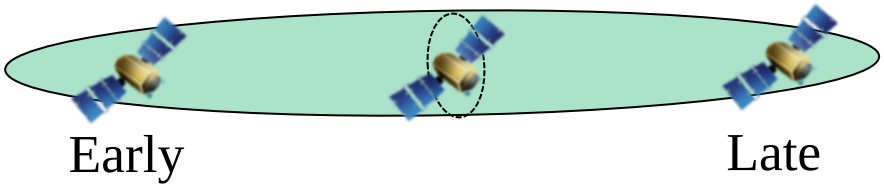
Less drag case
- Late
- More orbital energy

(not to scale)

- Can calculate time and energy differences with multiple OCMs:
  - Time difference: $\Delta t \cong \frac{\Delta \vec{r} \cdot \hat{v}}{|v|}$ (rectilinear motion assumption)
  - Energy difference calculated using (osculating) specific energy: $\varepsilon = \frac{v^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a}$

Time and Energy Offsets Between Predictions (con't)

- Changes to satellite energy and time offset sensitive to changes in:
  - Propagated atmospheric drag (as predicted atmospheric density already incorporated in propagated state vector)
  - Changing satellite position commensurate with position covariance

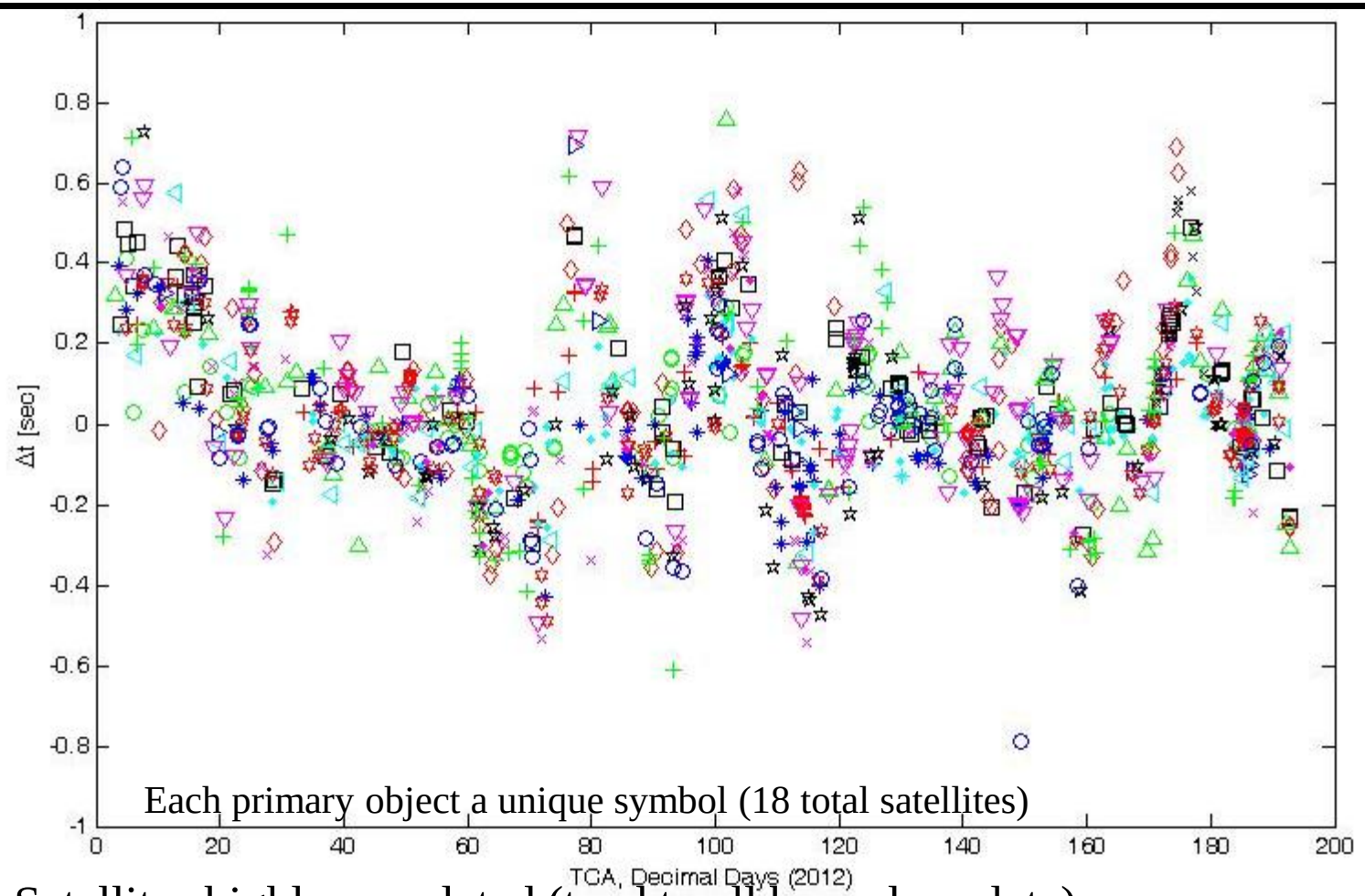


  - Potential ambiguity in interpreting results
    - Attribution to space weather may be impossible but may be able to establish plausibility

Empirical Evidence for Time Offsets: Preliminaries

- This presentation only examines Δt
  - Specific energy plots 'noisy' and highly sensitive to changes in state vector
- Time offset plots to follow:
  - Time offset plots in narrow altitude band (650 and 750 km) which includes the NASA A-train
    - Primary (operating) satellites, 6-7 days from TCA
    - Primary (operating) satellites, 2-3 days from TCA
    - Primary and secondary objects, 5-6 days from TCA
  - *x*-axis: TCA date in decimal days (2012)
  - Δt measured relative to last OCM received

Time Offset Plot: Primary Satellites, 6-7 days from TCA

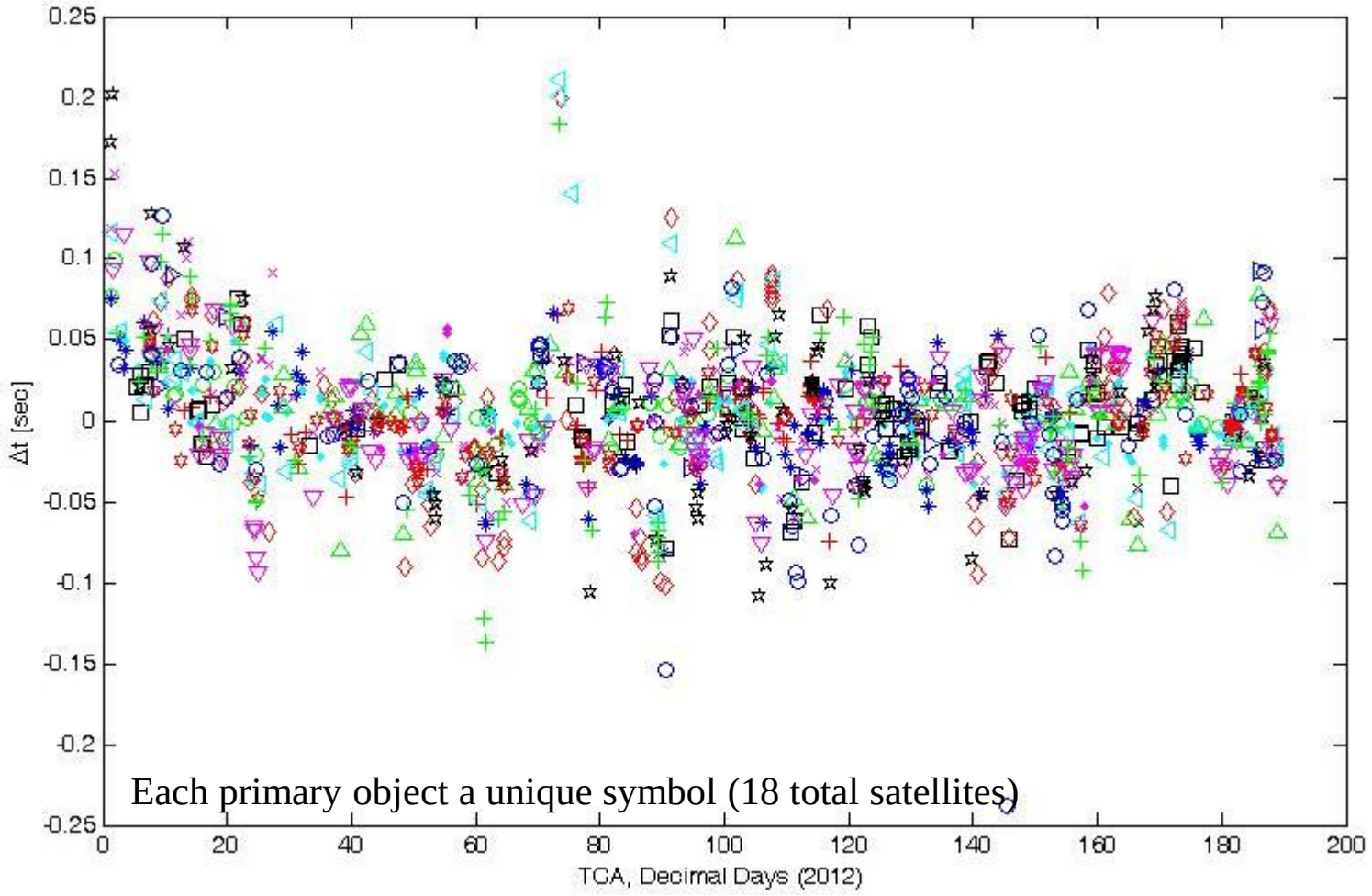


Satellites highly correlated (tend to all be early or late)

Very small spread in ballistic coefficient values

Indicative of differences in atmospheric density

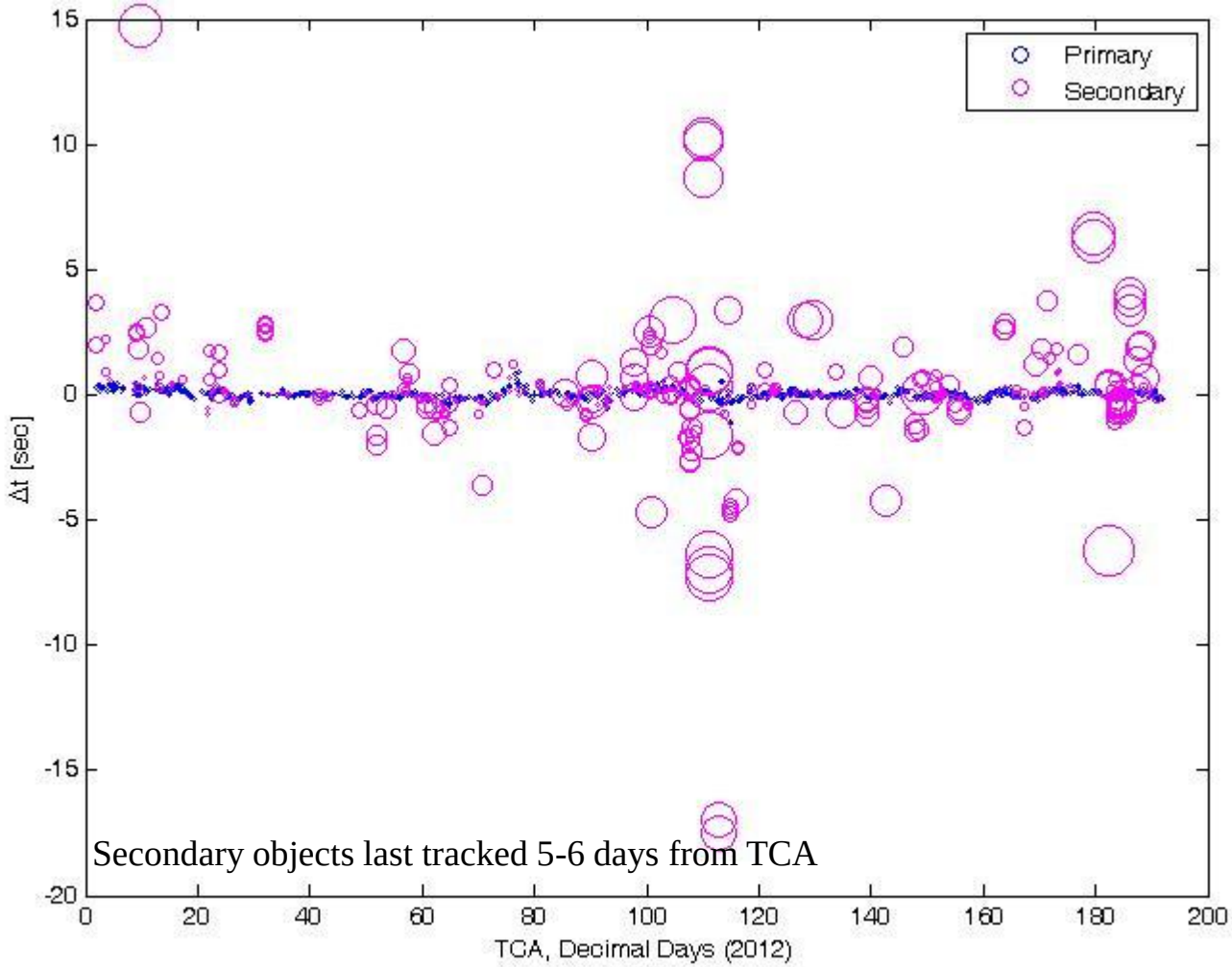
Time Offset Plot: Primary Objects, 2-3 days from TCA



Closer to TCA, magnitude of Δt gets smaller

Persistence of some of the correlations seen in previous slide

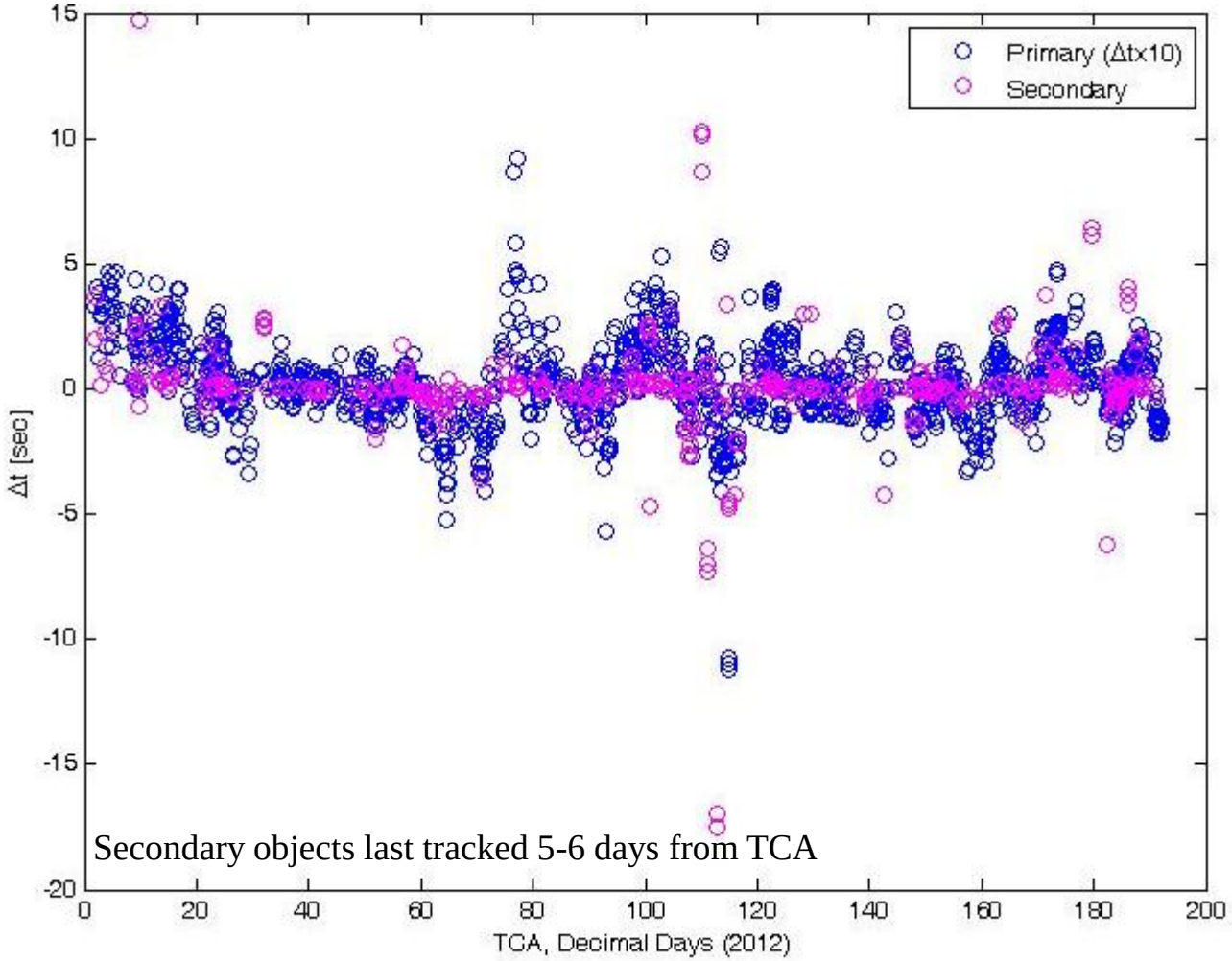
Time Offset Plot: Primary & Secondary Objects, 5-6 days from TCA



Symbol size proportional to ballistic coefficient value

Larger ballistic coefficient values have larger time offsets

Time Offset Plot: Primary & Secondary Objects, 5-6 days from TCA (con't)



Secondary objects last tracked 5-6 days from TCA

Primary object Δt scaled by factor of 10 for clarity

Correlation between sign of Δt changes for primary and secondary objects

Empirical Evidence for Time Offsets: Conclusions and Lead-in to Impact on CA

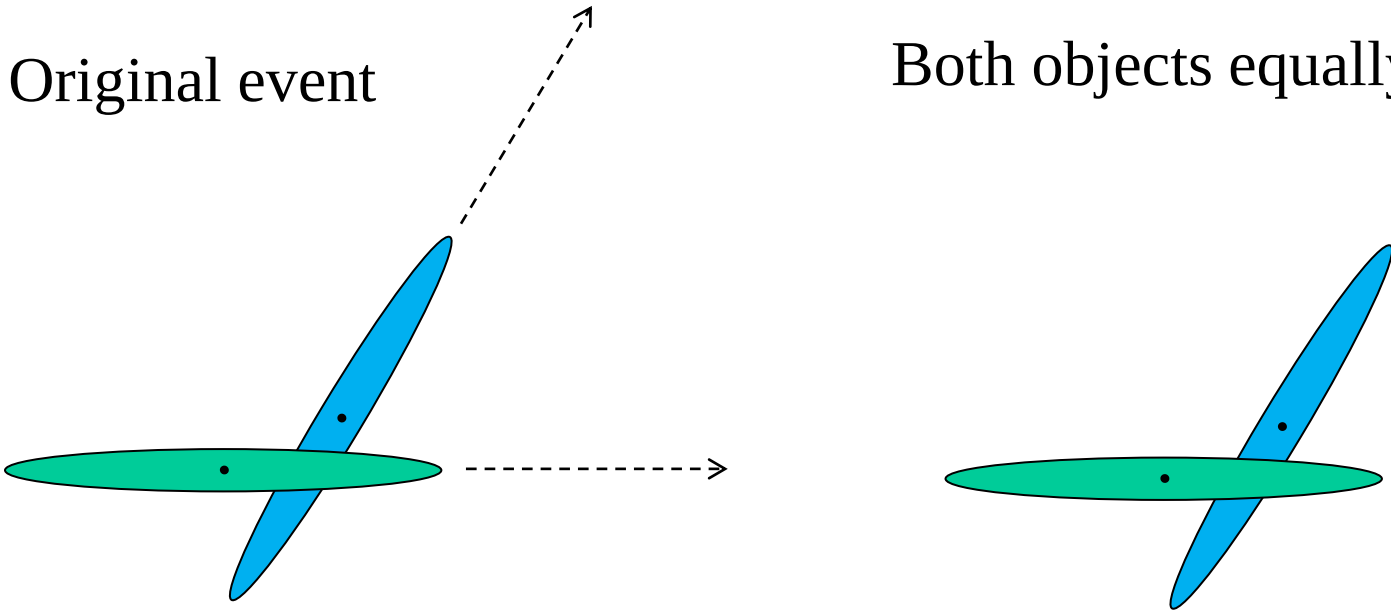
- Strong supporting evidence of changing atmospheric drag impact time offsets
  - Time offsets for payloads small but synchronized
  - Objects with larger ballistic coefficients show more severe time offsets as they are more strongly influenced by drag
- What is impact of a time offset on conjunction assessment?
  - Qualitative approach: 3 ‘cartoon’ scenarios
    - Both objects early/late by identical amount
    - “Head-on” event
    - “Non-head-on” event with different offset times
  - Quantitative approach

Qualitative Impact of Time Offsets: Scenario 1

Both objects early/late by identical amount:

Original event

Both objects equally late



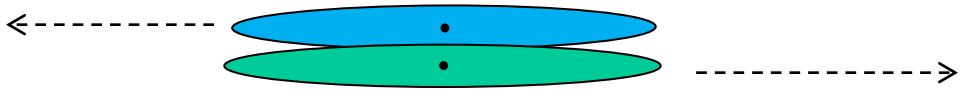
Slide intended to be viewed as custom animation (not captured in pdf version)

Results: TCA shifts, but at TCA the conjunction event looks identical

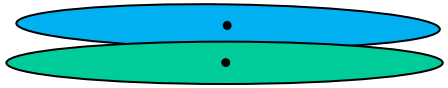
Qualitative Impact of Time Offsets: Scenario 2

"Head-on" event:

Original event



Both objects have time offsets (not necessarily identical)



Slide intended to be viewed as custom animation (not captured in pdf version)

Results: TCA shifts, but at TCA the conjunction event looks identical

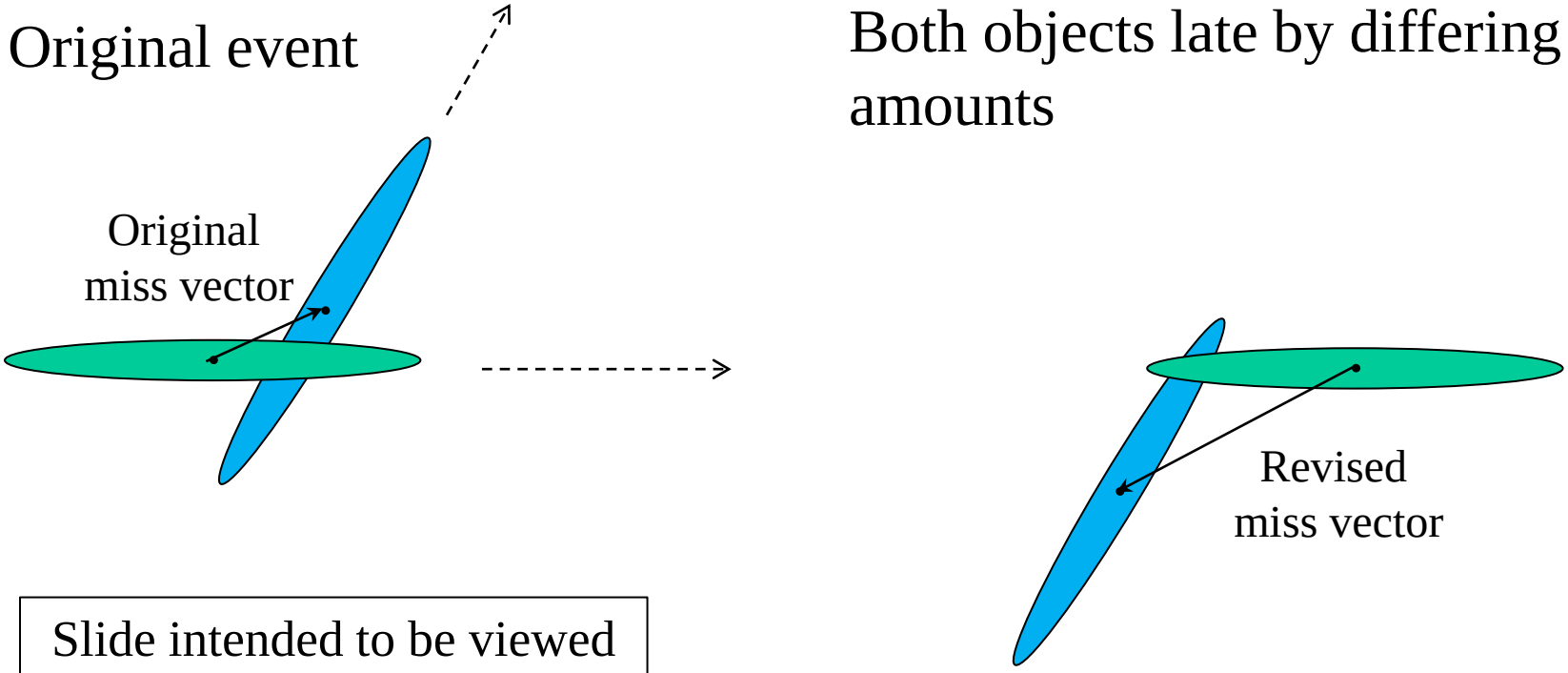
Qualitative Impact of Time Offsets: Scenario 3

"Non-head-on" event with different offset times:

Original event

Original miss vector

Both objects late by differing amounts



Slide intended to be viewed as custom animation (not captured in pdf version)

Results: TCA shifts, and conjunction event looks different at new TCA

Quantitative Impact of Time Offsets: Theory

- Miss component changes: related to time offsets
  - Use state vectors from OCM: $\vec{r}_p, \vec{v}_p, \vec{r}_s, \vec{v}_s$
  - WLOG, shift secondary object by Δt (net difference)
  - Rectilinear motion assumption:

$$\vec{r}_p'(t) = \vec{r}_p + \vec{v}_p t \qquad \vec{v}_p'(t) = \vec{v}_p$$

$$\vec{r}_s'(t) = \vec{r}_s + \vec{v}_s(t + \Delta t) \qquad \vec{v}_s'(t) = \vec{v}_s$$

  - New TCA: Find new t (relative to original TCA)

$$\vec{r}_{rel}' \cdot \vec{v}_{rel}' = (\vec{r}_s' - \vec{r}_p') \cdot (\vec{v}_s' - \vec{v}_p') = 0$$

$$= (\vec{r}_s + \vec{v}_s(t + \Delta t) - \vec{r}_p - \vec{v}_p t) \cdot (\vec{v}_s - \vec{v}_p)$$

$$= \vec{r}_{rel} \cdot \vec{v}_{rel} + \Delta t \vec{v}_s \cdot (\vec{v}_s - \vec{v}_p) + t|\vec{v}_s - \vec{v}_p|^2 = 0$$

$$t = \frac{-\Delta t \left(\vec{v}_s \cdot (\vec{v}_s - \vec{v}_p)\right)}{|\vec{v}_s - \vec{v}_p|^2} = \frac{-\Delta t (\vec{v}_s \cdot \hat{v}_{rel})}{|\vec{v}_{rel}|}$$

Quantitative Impact of Time Offsets: Theory (con't)

- Miss vector at new TCA:

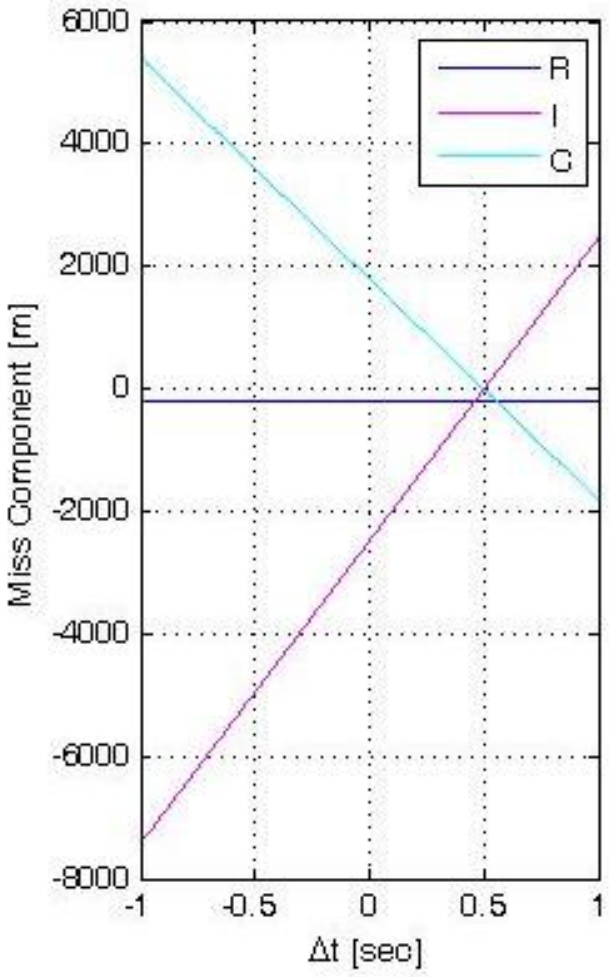
$$\vec{r}'_{rel} = \vec{r}'_s - \vec{r}'_p = (\vec{r}_s - \vec{r}_p) + \Delta t\,\vec{v}_s - \frac{\Delta t(\vec{v}_s \cdot \hat{v}_{rel})}{|\vec{v}_{rel}|}(\vec{v}_s - \vec{v}_p)$$

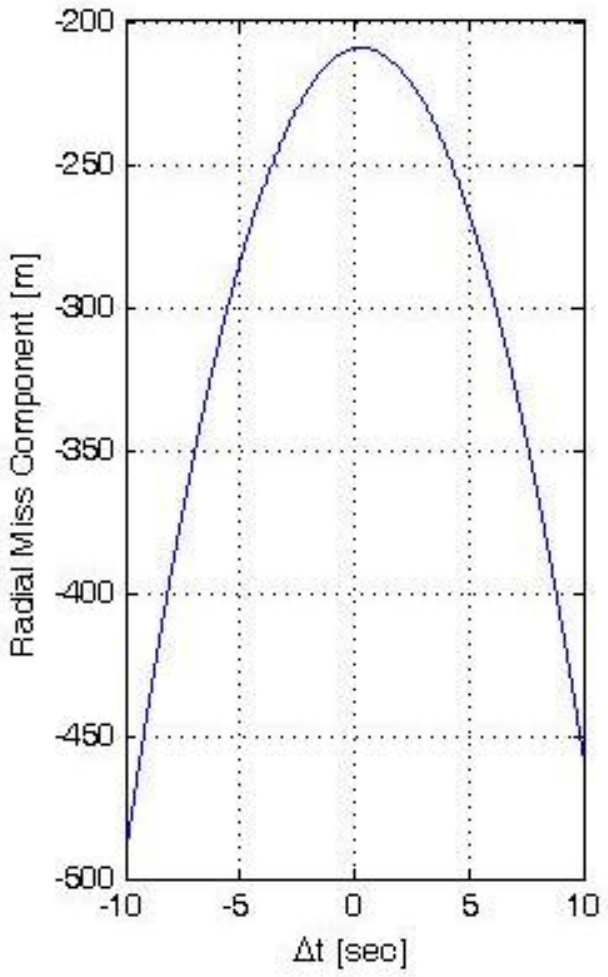
$$= \vec{r}_{rel} + \Delta t[\vec{v}_s - (\vec{v}_s \cdot \hat{v}_{rel})\hat{v}_{rel}]$$

Dependent on event geometry

- Strategy: vary Δt to generate family of possible misses
- Decompose into RIC miss components:
  - Radial: $\hat{R} = \hat{r}$
  - In-track: $\hat{I} = (\hat{r} \times \hat{v}) \times \hat{r}$
  - Cross-track: $\hat{C} = \hat{r} \times \hat{v}$ (Normal to orbital plane)

Quantitative Impact of Time Offsets: Example 1

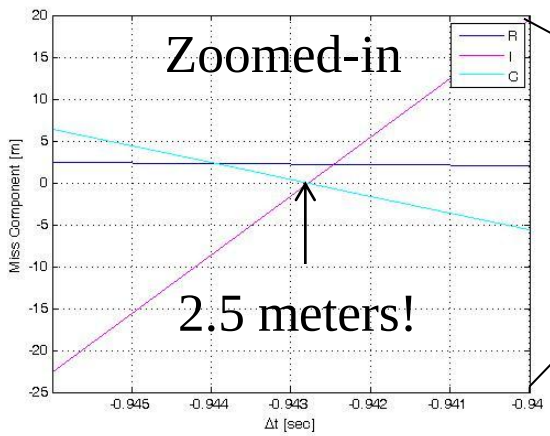


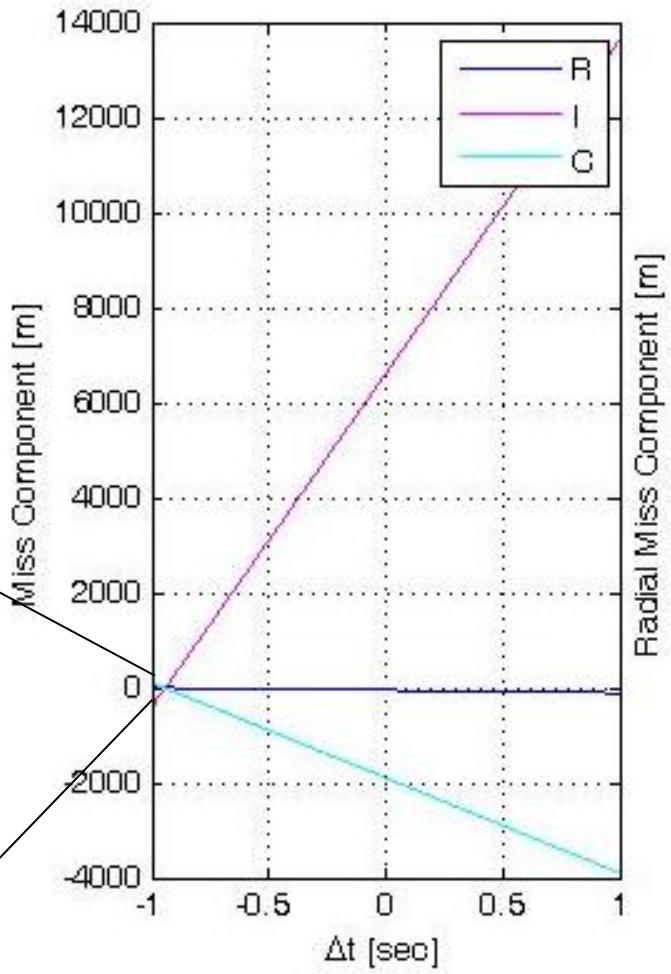


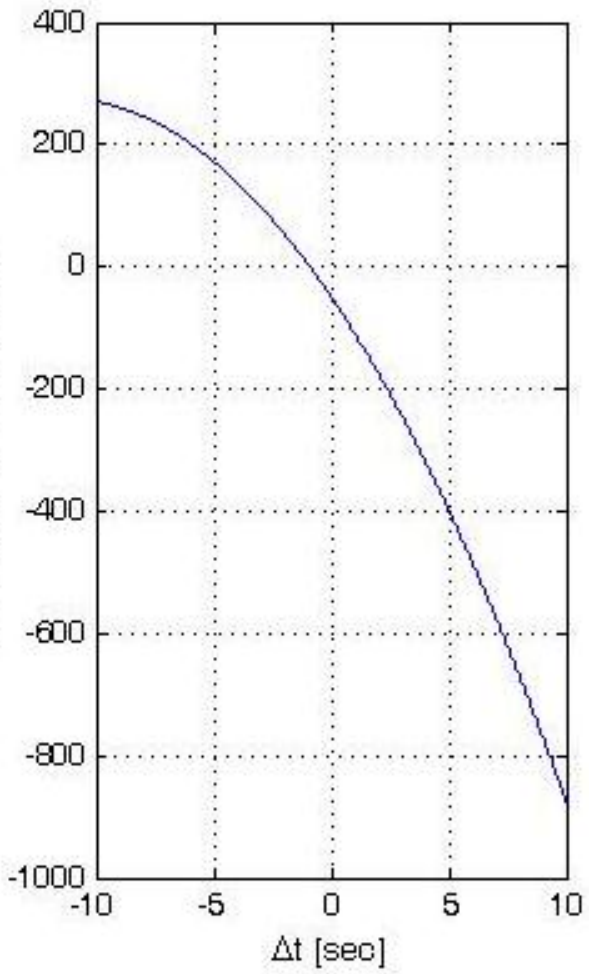
I,C zero crossing at ~0.5 sec
|R| only can increase

SAFE with respect to time offset

Quantitative Impact of Time Offsets: Example 2







There exists a time offset that is extremely dangerous. Might that time offset occur?

Quantitative Impact of Time Offsets: Results

- RIC miss components change in a coordinated manner
  - Varies based on conjunction geometry
- Varying time offset generates family of possible misses
  - Covers how conjunction might evolve over time
    - No predictive power – we don't know the actual time offset
  - Is there a time offset that would result in a potentially dangerous situation?
    - Does the radial miss get close to zero?
    - Do all miss components cross zero at around the same time offset?
- In process of evaluating utility of time offsets for evaluation conjunction assessment risk

Conclusions and Questions

- Using time offsets at TCA is a candidate technique to quantify how conjunction event might change
  - Time offsets are a physical effect on satellites from changing atmospheric drag predictions
  - Some conjunction events at substantially higher risk if there is a time offset
- Critical to give accurate risk assessments in light of changing space weather predictions
- Can we say anything about expected Δt values for changing space weather?
  - Can Δt be predicted or at least bounded?
  - Can the small Δt's of primary satellites be used as a predictor for the remainder of the catalogue?